A STUDY OF CONTROL OF WATER LOGGING THROUGH GROUND WATER MANAGEMENT

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INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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A STUDY OF CONTROL OF WATER LOGGING THROUGH GROUND WATER MANAGEMENT

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CERTIFICATE

Certified that this work entitled, 'A Study of Control of Waterlogging Through Ground Water Management' by Mr. Surendra Kumar has been carried out under my supervision and that this has not been submitted elsewhere for a degree.

January, 1986

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SURENDRA KUMAR

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ABSTRACT

Irrigation development is not an unmixed blessing. There are usually some undesirable environmental consequences such as waterlogging, salinity, increase in the incidence of malaria etc. It has been the experience in the past that there is a continuous rise in the ground water table when irrigation starts. An area is said to become waterlogged when the water table is less than $1\frac{1}{2}$ metres below ground level. Antiwaterlogging measures usually consist of drianage (surface and subsurface), embankment and other flood protection works, installation of shallow tube wells and pumping of water to lower the water table, lining of canals, suitable cropping pattern, land levelling, etc.

In the present work only one method of antiwaterlogging measure is studied, namely controlling of waterlogging by ground water management. A specific area namely Mahi Right Bank Canal (MRBC) Command area is taken up for the study. While actual waterlogging on a large scale in this area has not yet taken place, its likelyhood exists. A mathematical model is developed for the aquifers of the MRBC Command area to study different policies of ground water management for antiwaterlogging purpose.

The mathematical model was validated using the readily available data. Sensitivity analysis on the parameters S,T,Q and L was made. It was found that S,T are

not very sensitive compared to Q and L. In order to varity the effect of different boundary conditions on the results, three types of boundary conditions were studied. It was found that the different boundary conditions studied do not have much affect on the results when we move away from the boundary.

The validated model is then used for controlling the ground water table. One of the policies tested was to see how much pumpage is needed to lower the ground water table 3 metres below ground level where necessary. It was found that about 454 ~~544~~ MCM of water per year is required to be pumped for this purpose. This water, of course, is available for summer irrigation. A second policy of lowering ground water table to 6 m below ground level was also studied. This yields about 3960 ~~5840~~ MCM of water per year. This additional water can be used not only in Summer but also for Rabi irrigation.

CHAPTER I

INTRODUCTION

1.1 GENERAL

Agriculture is a major sector in Indian economy accounting for almost half of the national income and provides employment to about two-thirds of the work force. Accordingly, the greatest use of water resources has been for agricultural development which would benefit considerably by improvements of the management of Water Resources [Udai P.Singh,1984].

India's agriculture is basically dependent upon the south-west monsoon which is confined essentially to the period June to September. The rest of the year is practically dry in almost all parts of the country. Therefore the development of irrigation facility is necessary through the conservation of the monsoon rainfall in surface reservoir and as ground water which should be utilized in the non-monsoon seasons.

There is enough literature to say that irrigation was practised extensively in ancient India. The accent on efficient water management in ancient India is seen in the following writings of Magasthenes, the Greek Ambassador in the Court of Emperor Chandra Gupta in about 300 B.C. [IARI Research Bulletion, 1983].

''The whole country was under irrigation and very prosperous because of two crops grown in a year with irrigation facilities. The District officers measure the land and

inspect the sluices by which water is distributed in the branch canals (water courses) so that every one may share his fair share of benefit''.

It may be noted that irrigation plays a protective as well as productive role in the use of other agricultural inputs and thus becomes catalytic agent in enhancing the spread of ''green revolution''.

1.2 WATERLOGGING PROBLEM

Irrigation development, as with any other development, is not an unmixed blessing. There are usually some undesirable environmental consequences such as waterlogging, salinity, increases in the incidence of malaria etc. It has been the experience in the past that there is a continuous rise in the ground water table when irrigation starts. For example the water table which was about 30 metres below the ground level before the start of irrigation in the Sindh area in the Indus River Valley (present Pakistan) started rising at a rate of about 1/3 metre per year and presently large areas are waterlogged and saline. The opening of Ganga canal resulted in rise of water table in the Ganga-Yamuna Doab from a depth of 12.2 metres to about 4.6 metres in about 100 years. Similarly in the area commanded by the western Yamuna canal the water table rose at an average rate of 16 cm per year during the years 1932 to 1963 (Irrigation Commission Report, 1972).

An area is said to become waterlogged when the water table is less than $1\frac{1}{2}$ metres below G.L. High water table, heavy monsoon rainfall, perennial irrigation and flat nature of terrain all contribute to waterlogging. Anti waterlogging measures usually consist of drainage (surface and subsurface), embankment and other flood protection works (to check inundation of lands), installation of shallow tube-wells, lining of canals (to reduce seepage), suitable cropping pattern (using crops needing light irrigation), land levelling, etc.

1.3 ANTI-WATERLOGGING MEASURE

In the present work only one method of antiwaterlogging measure is studied, namely controling of waterlogging by ground water management. It is to be understood that in any given situation perhaps all the measures mentioned above will have to be undertaken to a lesser or greater degree depending upon the situation.

A specific area namely Mahi Right Bank Canal (MRBC) command area is taken up for the study. While actual water-logging on a large scale in this area has not yet taken place, its likelyhood exists. This area is selected because a lot of published data is available for this area. The main source of information is the publication of the Water Technology Centre, IARI: ''Resource Analysis and Plan for Efficient Water Management- A case study of the MRBC Command Area, Gujrat, 1983''.

Ground water was the major source of irrigation during the period prior to the commissioning of the MRBC irrigation

system. It continues to be so even after two decades of introduction of canal irrigation. The use of ground water has progressively increased over the years. In spite of this, the water table in the command area has been rising continuously at an ever increasing rate. Waterlogging has become a recurring problem in the command area [IARI Research Bull. 1983].

In the present study a mathematical model is developed for the aquifers of the MRBC Command area to study different policies of ground water management for anti-waterlogging purpose.

CHAPTER II

THE STUDY AREA

2.1 LOCATION

Mahi Right Bank Canal Command area is situated in the heartland of the proposed Narmada high level canal command area in Gujrat which has an estimated potential of over two million hactares (see Fig. 2.1).

Kaira district, in which the MRBC command area is located, is one of the 19 districts of Gujrat State. It lies between 22°7' and 23°18' north latitudes and 72°25' and 73°37' east longitudes. The geographical area of the district is 6888 sq. km., which is about 3.67 percent of the total area of the State.

2.2 GEOLOGY

According to geologists, the MRBC Command area is covered by the alluvial deposits carried by Mahi and Sabarmati rivers. The area is the result of the continuous degradation of the main rocks namely, phyllites, schists and quartzite.

The alluvial deposits overly the Deccan trap basements. The total thickness of alluvial deposits which are unconsolidated varies between 30 to 150 metres from east to south-west.

A typical cross section of the area is shown in the Figure 2.5. It indicates that the aquifer in the MRBC command area consists of gravel and sand with an average thickness of about 30 metres and varying upto 60 metres. A distinct

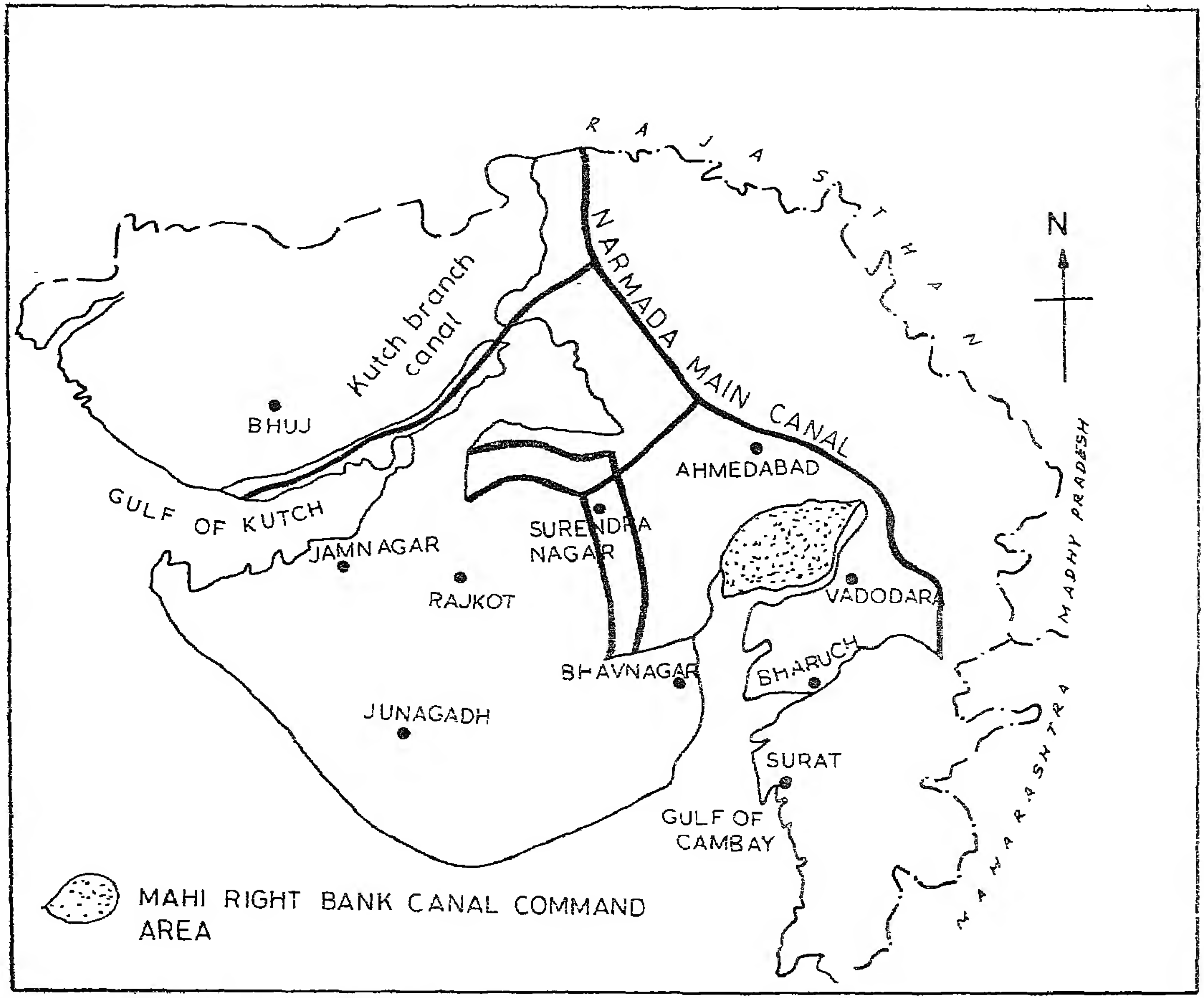

Fig. 2·1 Location map of the study area

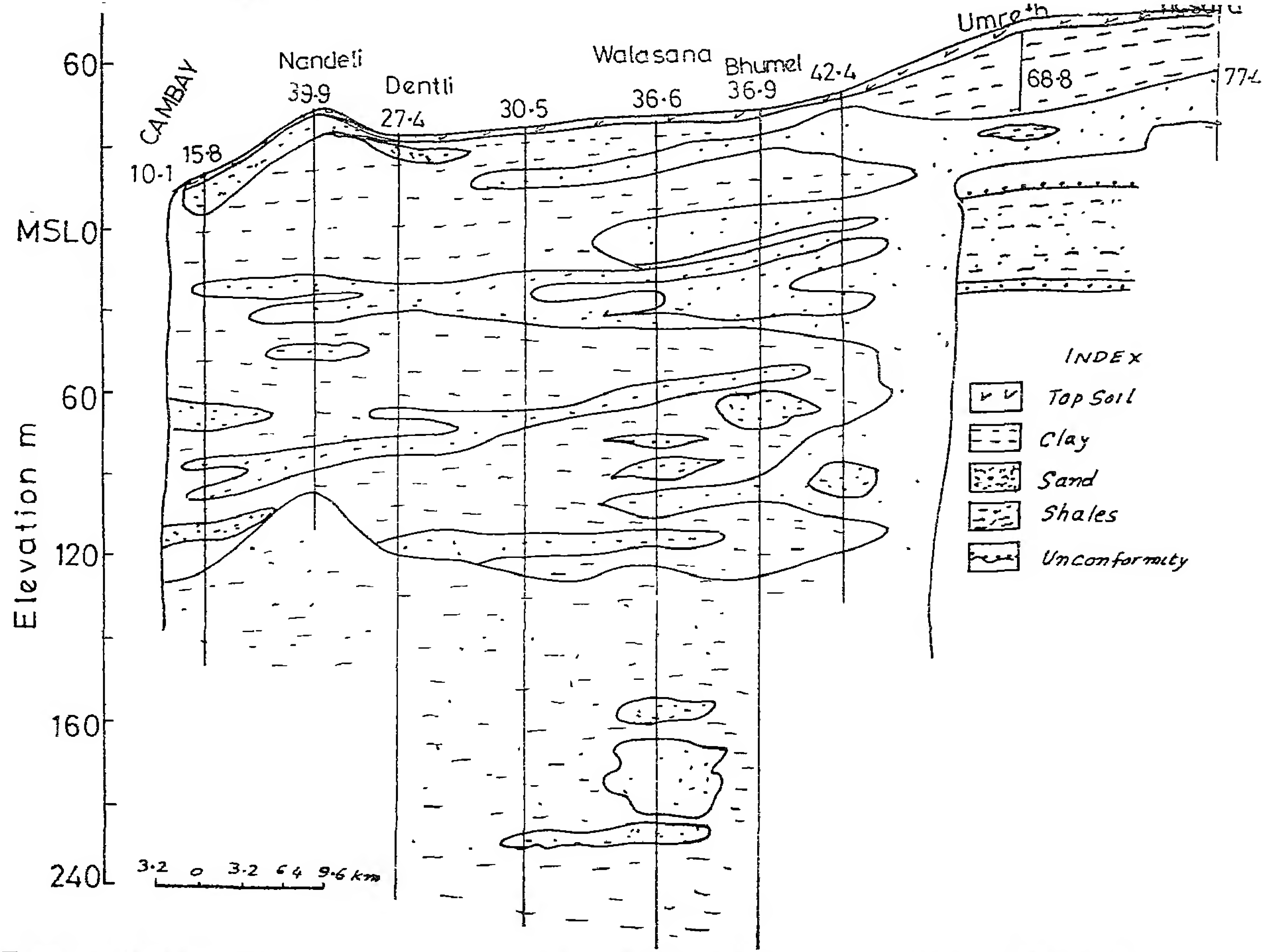

Fig.2.5 Lithological cross section of the study area across Cambay and Thasara

water table aquifer of about 10 to 15 metres thickness overlying the main confined aquifer seperated by layers of clay and kankar is seen. In general clays are mixed with kankar and sandy material.

2.3 HYDRO-METEOROLOGICAL CHARACTERISTICS

2.3.1 RAINFALL

Indian agriculture is largely dependent on monsoons and it greatly suffers due to erratic distribution of rainfall over the year and its unpredictable behaviour. The failure of monsoon in a year or its late arrival considerably affects the economy of the nation [Singh, R.L. 1978].

The average annual rainfall of the MRBC Command area is 823 mm, spread over 35 rainy days . 96 percent of the annual rainfall is received during south-west monsoon.

The Indian Meteorological Department maintains the records of rainfall. A record of monthly rainfall for the year 1976-79 is given in Table 2.1.

2.3.2 DRAINAGE

The Mahi Right Bank Canal Command area is characterised by a generally flat topography, restricted natural drainage, comparatively heavy soils and semi-arid climate, all of which are conducive to the development of water logging and salt accumulation [IARI Research Bull. 1983].

The possible causes of the continuing problem of water logging are attributed to the following:

TABLE 2.1 : MONTHLY RAINFALL IN THE STUDY AREA DURING THE YEARS 1976-1979

Year	Sl. No.	Location of raingauge station	Months							
			May	June	July	August	September	Oct.	November	Total
1	2	3	4	5	6	7	8	9	10	11
1976	1.	Thasra	-	329.00	604.00	457.00	71.00	-	88.00	1549.00
	2.	Anand	-	368.25	368.00	384.50	127.70	-	89.25	1337.75
	3.	Nadiad	-	357.50	408.25	501.80	92.50	-	80.25	1420.30
	4.	Cambay	-	497.96	351.90	458.40	103.80	-	61.80	1492.86
	5.	Petlad	-	373.57	451.00	800.00	187.00	-	147.00	1967.57
	6.	Matar	-	250.50	493.75	487.25	81.50	-	-	1313.00
	7.	Borsad	-	374.00	281.37	522.50	146.50	-	58.30	1382.67
	8.	Sojitra	-	422.50	421.10	517.85	184.25	-	49.20	1594.90
		Average	-	369.16	422.42	517.29	124.28	-	71.73	1507.26
1977	1.	Thasra	42.00	401.00	459.00	303.00	65.00	-	-	1270.00
	2.	Anand	-	490.50	484.50	173.75	77.01	-	-	1225.76
	3.	Nadiad	-	357.05	484.55	173.25	155.50	-	-	1170.35
	4.	Cambay	9.70	273.60	481.25	47.38	45.30	-	-	857.23
	5.	Petlad	13.00	256.50	646.00	170.00	115.00	-	-	1200.50
	6.	Matar	-	304.55	186.00	158.00	-	-	-	648.55
	7.	Borsad	-	222.00	480.00	95.70	71.35	-	27.00	900.65
		Average	9.24	329.31	460.71	160.73	75.59	-	3.86	1039.00

Contd...

Table 2.1 contd...

1	2	3	4	5	6	7	8	9	10	11
1978	1.	Thasra	-	99.00	136.00	520.00	-	-	-	805.00
	2.	Anand	-	19.30	172.00	523.30	26.00	-	57.60	797.60
	3.	Nadiad	-	63.25	168.75	406.93	-	-	-	538.93
	4.	Cambay	-	67.40	189.32	646.12	-	-	-	902.84
	5.	Petlad	-	139.00	221.05	744.00	-	-	-	1104.05
	6.	Matar	-	35.00	211.00	477.00	-	-	-	723.00
	7.	Borsad	-	62.01	248.09	496.13	22.01	-	-	828.24
	8.	Sojitra	-	32.00	210.00	582.00	5.00	-	17.60	846.00
		Average	-	64.62	200.78	549.435	6.63	-	9.25	830.71
1979	1.	Thasra	-	210.05	131.05	370.00	39.00	3.00	155.00	908.10
	2.	Anand	-	94.86	72.20	473.80	2.00	28.00	209.57	880.43
	3.	Nadiad	-	140.25	125.25	326.50	-	2.50	87.00	681.40
	4.	Cambay	-	296.30	93.10	483.84	26.00	6.08	169.80	1075.12
	5.	Petlad	-	69.00	189.00	430.00	10.00	-	124.00	822.00
	6.	Matar	-	145.00	66.00	418.50	-	5.00	119.00	753.50
	7.	Borsad	-	178.00	104.00	357.00	15.00	-	228.00	882.50
	8.	Sojitra	-	144.00	126.00	429.00	-	12.00	133.00	844.00
	9.	Limbasi	-	163.00	107.00	348.60	15.00	6.50	127.25	767.35
		Average	-	160.05	112.62	404.19	11.89	7.00	150.20	846.06

Average annual rainfall for the MRBC command area during 1976-80: 1056 mm

Source: Department of Irrigation, MRBC, CADA, Nadiad.

1. Inadequate number and capacity of drains to effectively dispose off the excess rain water from the cropped fields.
2. Improper irrigation in the command area.
3. Seepage from canals system and consequent rise of water table.
4. Inadequate maintenance of the drains.

A systematic approach on the provision of drainage facilities in the MRBC command area was initiated in 1971. The details of the drianage system are given in Fig. 2.2.

2.3.3 CLIMATE

2.3.3.1 TEMPERATURE AND HUMIDITY

The climate of Mahi Right Bank Canal Command area is semi-arid. It is characterised by hot summer and general dryness, except during the south west monsoon season which experiences heavy rain. It is divided into four distinct seasons, cold season from Dec. to Feb. is followed by hot summer from March to middle of June. Mid June to Sept. is south-west monsoon season, October and November post monsson season.

India Meteorological department has not maintained meterological observatory within the command area for recording temperature, humidity, sunshine and other weather data. The information on temperature presented here is based mainly on the records of the observatory at Baroda close to MRBC area.

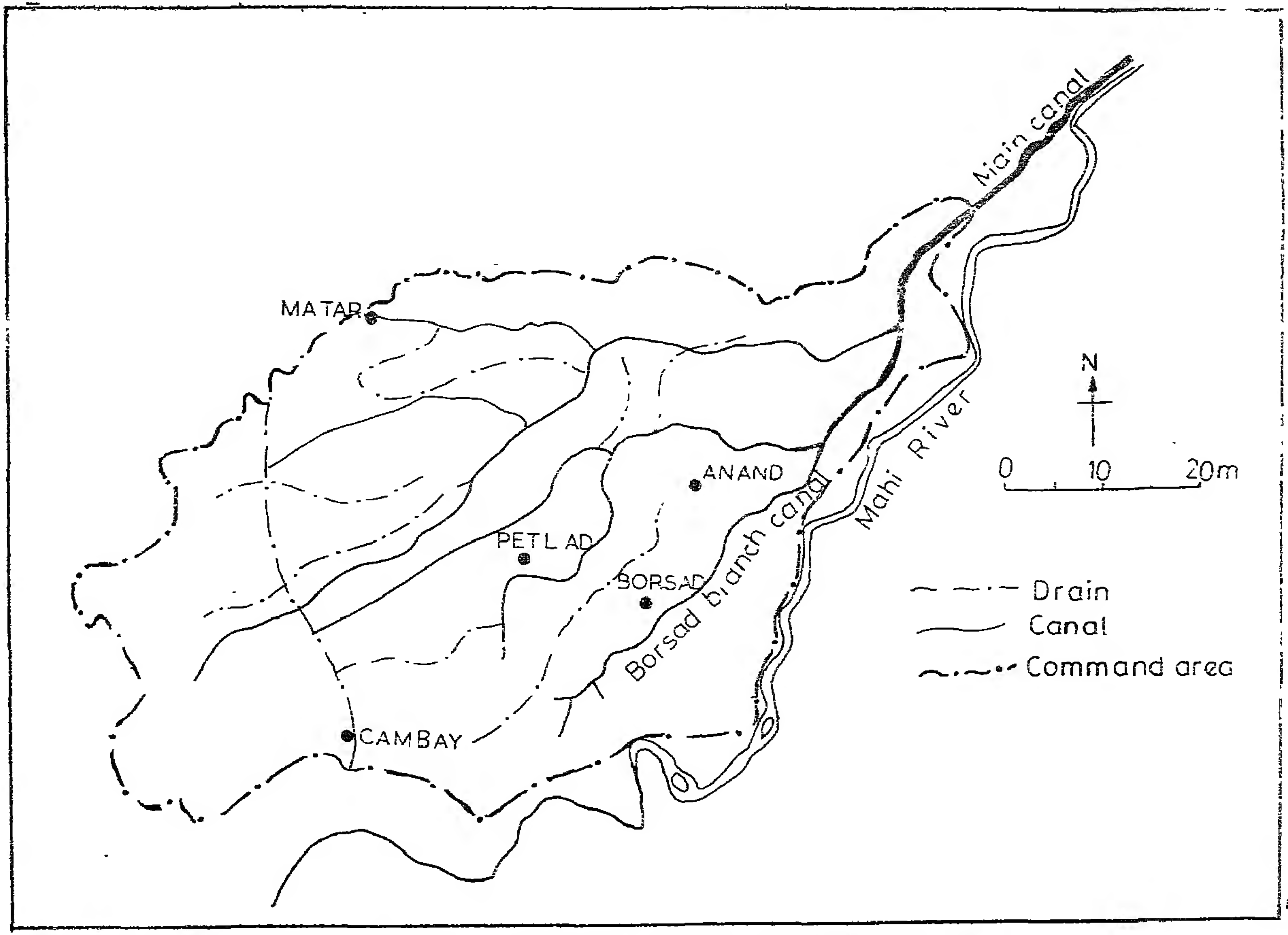

Fig.2·2 Main drains provided in the study area

During the period from March to May there is continuous increases in temperature. May is generally the hottest month, the mean daily maximum temperature being 41^{o}C and mean daily minimum temperature about 26^{o}C. There is appreciable drop with the onset of monsoon season. January is generally the coldest month with the mean daily maximum temperature of about 30^{o}C and mean daily minimum temperature about 11^{o}C. During the cold waves, the temperature sometimes drops to 2 to 3^{o}C.

Humidity is generally high during the south-west monsoon season. April to June is the driest part of the season when the relative humidity is 46 to 91 percent in the morning and 16 to 75 percent in the afternoon.

2.3.3.2 WIND

During most of the months in the year, the winds are generally light, ranging from 2.6 km/hr to 9.8 km/hr. Comparatively strong wind blow in summer months.

2.3.4 PAN-EVAPORATION

Pan evaporation values for the study area are not available. However, some values are available for a neighbouring area, namely the Vasad area. Table 2.2 gives the pan evaporation data, observed at Central Institute of Soil and Water Conservation, Vasad [IARI Research Bull. 1983].

TABLE 2.2 : DATA OF AVERAGE DAILY EVAPORATION OF VASAD

Years	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
	Average daily Evaporation(mm)											
1958	–	–	–	–	12.9	10.2	3.4	3.9	2.3	3.8	6.9	6.8
1959	6.9	8.4	13.2	16.5	19.5	11.9	2.9	3.1	3.0	4.9	6.3	7.8
1960	8.3	9.3	9.4	14.3	14.5	10.5	5.2	2.3	4.0	3.3	9.9	8.2
1961	10.8	11.1	16.6	11.5	17.2	11.8	3.4	3.1	2.4	5.9	7.0	8.2
1962	5.5	6.3	8.9	11.6	13.7	11.6	6.0	4.4	4.9	7.1	5.5	4.4
1963	5.7	7.5	8.1	11.1	12.1	10.9	4.7	4.5	7.0	6.2	4.6	4.6
1964	5.0	7.2	8.7	9.6	11.2	10.6	6.4	5.1	4.8	5.2	5.8	6.2
1965	4.9	7.7	8.3	10.1	11.4	12.3	5.3	4.2	5.9	7.5	6.3	5.1
1966	6.0	7.8	9.9	11.5	12.1	8.5	6.6	6.5	6.7	5.7	4.9	5.7
1967	6.7	8.6	8.9	12.4	10.8	9.5	4.9	5.0	4.9	7.3	4.7	4.3
1968	4.4	5.9	8.5	10.0	11.2	11.0	5.8	4.2	5.5	5.4	5.3	4.6
1969	5.4	6.2	8.6	9.8	14.4	8.5	6.0	3.3	4.0	5.2	5.1	5.1
1970	5.1	6.1	8.6	10.4	12.5	9.2	7.4	5.4	3.8	5.1	5.4	4.7
1971	5.5	6.6	9.9	13.0	12.9	8.8	4.5	3.5	4.6	5.0	5.3	5.2
1972	4.9	6.3	8.9	12.9	15.1	10.8	6.7	5.6	6.6	7.1	5.6	4.8
1973	5.4	7.4	10.4	12.5	13.4	10.2	5.0	5.0	3.7	4.1	3.2	3.8
1974	3.2	5.2	6.1	7.5	8.4	8.5	5.1	4.6	5.6	3.8	4.3	3.6
1975	3.9	5.7	7.5	9.6	10.1	6.8	4.0	2.8	3.2	3.9	3.3	2.8
1976	2.9	4.7	6.5	7.5	8.4	5.5	3.8	2.4	3.2	4.1	2.9	2.9
1977	3.3	4.7	6.9	7.7	8.1	6.0	3.0	2.9	4.2	4.2	3.6	2.4
1978	3.5	4.8	6.6	7.8	8.5	5.6	3.1	2.7	4.1	4.5	3.8	3.3
1979	3.5	4.1	6.6	8.5	9.8	8.6	4.4	2.8	4.5	5.0	2.3	2.8
1980	3.8	5.3	7.0	8.8	9.7	4.9	3.7	2.9	4.5	4.5	3.8	3.0

– Record not available.

Source: Central Institute of Soil and Water Conservation, Vasad

2.4 WATER TABLE

The ground water levels in the MRBC command area are being observed since the introduction of canal irrigation. The water level data of open wells and shallow tube wells were collected twice in a year to represent the pre-monsoon and post-monsoon water levels. Based on the analysis of pre- and post-monsoon water levels for the period 1961 to 1973, it was observed that on an average, the water level rise was 0.28 metres per year [IARI Research Bull. 1983]. There are some regions in the command area where the water table rise was observed to be much steeper. The trend of water table rise at selected locations is shown in Fig. 2.3 [IARI Research Bull. 1983].

It may be seen that by 1980 the water table rose considerably in the northern and north western parts of the command area as compared to the pre-irrigation period. The changes in the depth to water table in the same region during the pre and post monsoon period in the year of 1980 are presented in Fig. 2.4.

Table 2.3 gives the area with different ranges in depth to water table during pre-monsoon periods in 1958 and 1981 in the MRBC command area (upstream of Alang drain) and Table 2.4 gives the areas under different groups of depths to water table during pre-monsoon and post-monsoon periods for the year 1980. It is seen from these that while the waterlogging may not be acute at present (1980), it is on the

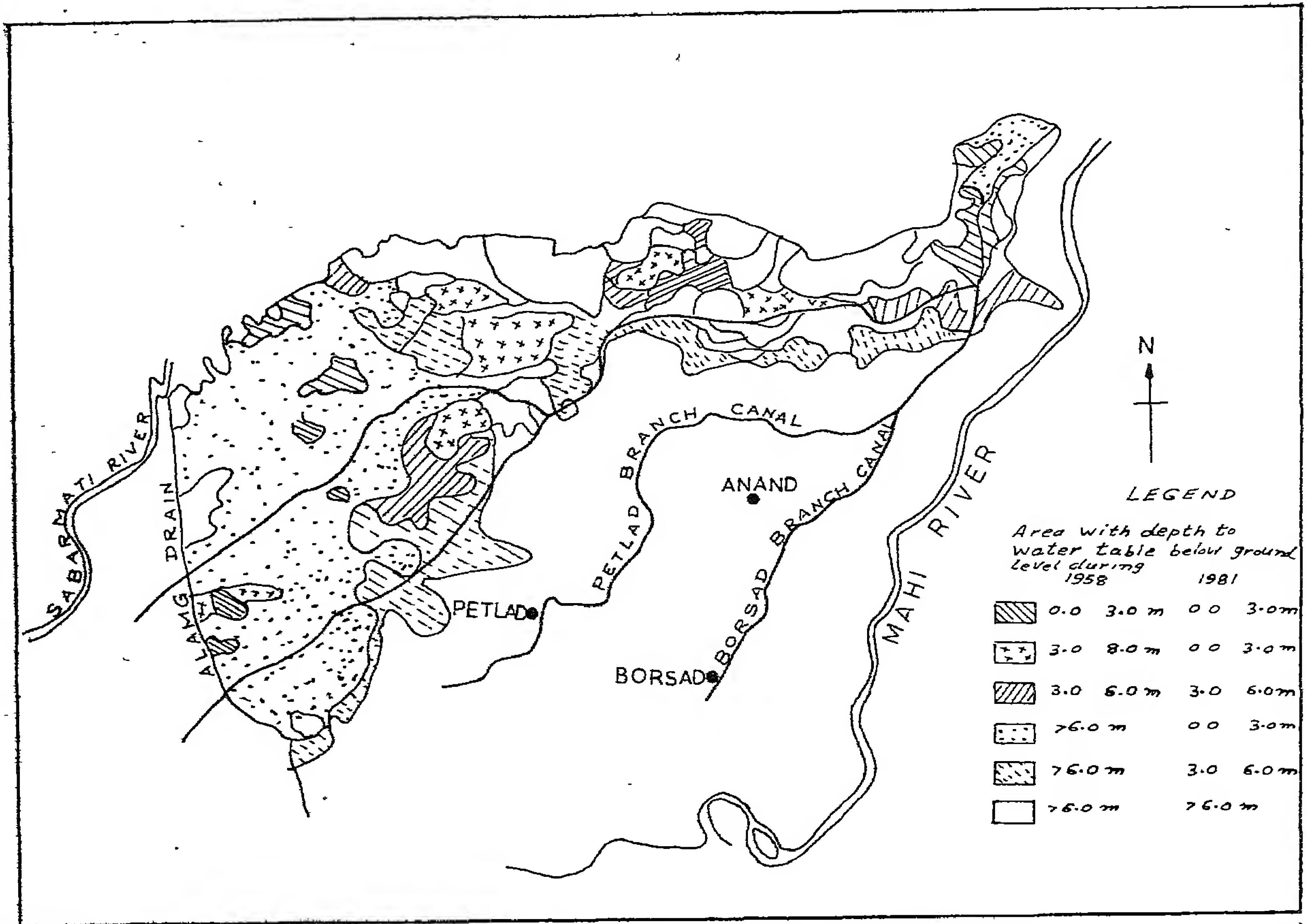

Fig. 2.3 Depth to water table (premonsoon)

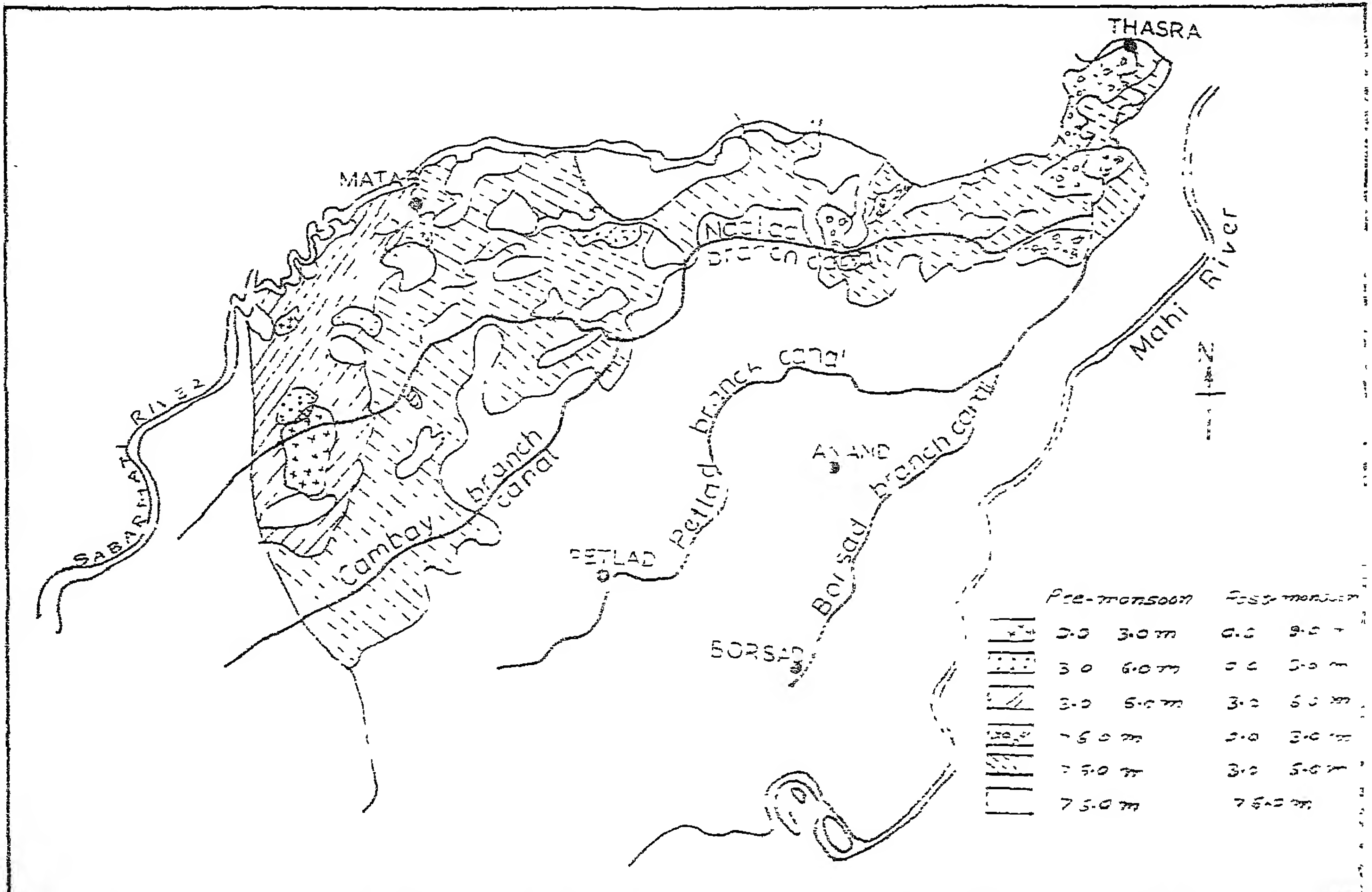

Fig.2·4 Pre and post monsoon water table depths for 1980

TABLE 2.3: AREAS WITH DIFFERENT RANGES IN DEPTH TO WATER TABLE DURING PRE-MONSOON PERIODS IN 1958 AND 1981 IN THE MRBC COMMAND AREA (UPSTREAM OF ALANG DRAIN).

Depth to water table from ground surface m	Area covered			
	1958		1981	
	ha	Percent of total	ha	Percent of total
1.5	–	–	475	0.20
1.5 to 3.0	2,643	0.90	9,360	3.20
3.0 to 6.0	18,058	6.10	83,338	28.30
6.0 to 9.0	15,277	5.20	33,500	11,40
9.0	2,57,882	87.80	1,67,207	56.90
Total	2,93,860	100.00	293,860	100.00

Source : Report on water conditions in MRBC Area, Soil Survey Division, Dept. of Irrigation, Govt. of Gujarat, 1981.

TABLE 2.4 : AREA UNDER DIFFERENT GROUPS OF DEPTH TO WATER TABLE DURING PRE-MONSOON AND POST-MONSOON PERIODS FOR THE YEAR 1980 IN THE STUDY COMMAND AREA (UPSTREAM OF ALANG DRAIN)

Depth to water table from ground surface	Area covered			
	Pre-monsoon, 1980		Post-monsoon, 1980	
m	ha	Percent of total	ha	Percent of total
1.5	250	0.10	10,725	3.70
1.5 to 3.0	7,780	2.60	51,335	17.50
3.0 to 6.0	71,025	24.20	48,911	16.60
6.0 to 9.0	42,077	14.30	29,009	9.90
9.0	1,72,728	58.80	1,53,830	52.30
Total	2,93,860	100.00	2,93,860	100.00

Source: Report on water table conditions in MRBC Area. Soil Survey Division, Dept. of Irrigation, Govt. of Gujarat, 1981.

TABLE 2.5 : MONTHLY RELEASES OF IRRIGATION WATER AT THE WANAKBORI WEIR HEADWORKS MRBC SYSTEM (BASED ON DAILY OBSERVED VALUES).

Sl. No.	Month	1976-77 ha-m	1977-78 ha-m	1978-79 ha-m	1979-80 ha-m	1980-81 ha-m
1.	June	1,410	0	0	0	0
2.	July	16,972	9,374	16,846	16,662	24,747
3.	August	8,944	24,433	31,683	26,331	29,286
4.	September	13,933	26,995	33,387	38,202	43.667
5.	Oct.	23,295	26,640	32,352	25,371	35,430
6.	Nov.	8,573	11,698	10,883	6,475	9,609
7.	Dec.	6,723	9,996	4,362	3,143	8,623
8.	Jan.	2,224	7,680	6,894	5,751	11,166
9.	Feb.	1,798	4,738	7,617	5,584	11,126
10.	March	1,055	2,705	3,019	5,577	11,199
11.	April	0	0	0	7,005	0
12.	May	0	0	0	4,560	0
Total	Year	84,927	1,24,189	1,47,043	1,44,661	1,84,847

Average annual flow for the period 1976-77 to 1979-80: 1252 MCM

Source: Department of Irrigation, MRBC, CADA, Nadiad.

increase as more and more area is coming within the water table depth of about 0 to 1.5 metres below ground level. Hence suitable measures require to be taken to control this. One of the metnods is proper ground water management.

2.5 IRRIGATION

Irrigation water is drawn from the MRBC irrigation distribution network as well as from the ground water basin. Irrigation from other independent sources, such as tanks, local streams etc. is negligibly small. The total volume of irrigation water delivered through the MRBC distribution network during period June to May for the years 1976-77 to 1979-80 are shown in Table 2.5.

The area irrigated by wells during the years 1976-77 to 1979-80 for the period June to May is presented in Table 2.6.

TABLE 2.6 : AREA IRRIGATED AND DRAFT FROM WELLS IN MRBC COMMAND AREA

Year	Kharif ha.	Draft mm+	Annual area ha	Draft mm+
1976-77	53411	67	91794	104
1977-78	54075	68	107002	121
1978-79	66822	84	133510	151
1979-80	69371	87	120575	136
Average	60920	76	113220	128

+ Depth of water distributed over the GCA of 31600 ha.

It is evident that at the present rate of development in irrigation activity, the ground water table will continue to rise and will result in waterlogging. It is therefore necessary to control it. Management of groundwater through proper development of ground water will change the ground water regime and the incipient conditions of waterlogging are controlled. The exact impact of ground water development in different regions can be assesed by formulating a computer based ground water management model.

2.6 AQUIFER CHARACTERISTICS

In the command area pump-test analysis has been done in several wells, these tests shows that coefficient of transmissivity lies between 186 m^2/day to 6830 m^2/day with the higher values occuring in the eastern parts and lower values in the western parts. Long duration pumping tests conducted at selected sites indicated that the storage coefficient values of the aquifers in the MRBC command area range between 1.5×10^{-4} to 4.17×10^{-3}. These tests also indicated that the aquifer is leaky in most of the area. The average values of leakage coefficient (K'/b') was observed to be 0.0032 ~~0.0016~~ day^{-1}. Table 2.7 gives depth, thickness and coefficient of permeability of aquifers at various locations.

TABLE 2.7: RANGE OF GEOHYDROLOGICAL PARAMETERS IN THE DIFFERENT TALUKS COMPRISING THE MRBC COMMAND AREA

	Taluk	Depth (m)	Thickness of aquifer (m)	Hydraulic conductivity (m/day)
1.	Borsad	91-167	26-62	40-105
2.	Thasra	40-63	10-22	80-230
3.	Anand	52-192	13-48	34-88
4.	Cambay	110-154	21-60	31-70
5.	Nadied	134-152	27-61	30-75
6.	Petlad	97-166	28-70	35-85
7.	Matar	152-155	18-40	21-52

CHAPTER III

GROUND WATER MANAGEMENT MODEL

Several methods are used by ground water hydrologists to tackle ground water problems. Some of these are (1) Analytical methods (2) Analog methods (3) Digital methods and (4) Sand model methods etc.

3.1 ANALYTICAL METHODS

Analytical methods are used for aquifers having uniform properties. These properties, in general, are

1. Coefficient of transmissibility
2. Coefficient of storage
3. Coefficient of leakage

The mathematical equations used for simplified aquifer systems are given in Table 3.1.

TABLE 3.1: SIMPLE ANALYTICAL MODEL EQUATIONS

Sl.No.	Mathematical Model Equations	Applied to
1.	$s = \frac{Q}{4\pi T} W(u)$ $u = \frac{r^2 S}{4Tt}$	Isotropic nonleaky artesian aquifer with fully penetrating wells and constant-discharge conditions
2.	$s = \frac{Q}{4\pi T} W(u, \frac{r}{m}, \gamma)$ $u = \frac{\gamma^2 S}{4Tt}$	Isotropic nonleaky artesian aquifer with partially penetrating wells and constant discharge conditions

Contd.....

Table 7 contd...

Sl.No.	Mathematical Model Equations used in metric system	Applied to
	$\eta = \dfrac{m - m_d}{m}$	
3.	$s = \dfrac{Q}{4\pi T} W(u, \dfrac{r}{B})$ $\dfrac{r}{B} = \dfrac{r}{\sqrt{T/(\frac{K'}{m'})}}$ $u = \dfrac{r^2 S}{4T\,t}$	Isotropic leaky artesian aquifer with fully penetrating wells and constant discharge conditions without water released from storage in aquitard.
	$s = \dfrac{Q}{2\pi T} K_0 (\dfrac{r}{B})$	
4.	$s = \dfrac{Q}{4\pi T} W (u_{ay}, \dfrac{r}{D_t})$ $u_a = \dfrac{r^2 S}{4\,T\,t}$ $u_y = \dfrac{r^2 S_y}{4\,T\,t}$ $\dfrac{r}{D_t} = \dfrac{2.73\,r}{\sqrt{T/D_i S_y}}$ $D_i = \dfrac{(r/D_t)^2 (\frac{1}{u_y})}{4\,t}$	Isotropic water-table aquifer with fully penetrating wells and constant discharge conditions.

where,

s = dradown in meters,

Q = discharge in m^3/day

T = coefficient of transmissibility of aquifer in m^2/day

S = coefficient of storage of aquifer, fraction

r = distance from production well to observation point in metres

t = time after pumping started in days

m = saturated thickness of aquifer in meters

m_d = distance from top of aquifer to top of screen in meter,

K' = coefficient of permeability of aquitard in m/day

m' = saturated thickness of aquitard in meters

Sy = specific yield of aquifer in meters

k_o = Besselfunction of the zeroth order and second kind.

$W(u)$, $W(u,r/B)$, $W(u,r/Dt)$, $W(u,r/B,\nu)$ are well functions.

Principle of superposition is used in applying the analytical methods mentioned above. Since the approximate governing differential equation used in the simplified models is linear, the effects of pumping of or recharge from several wells are superposed. If the number of wells operating in an aquifer is small, this addition can be done manually. If the number of wells is large then recourse is taken to digital computers.

Boundary conditions are usually taken into account in these analytical methods by the method f images [Walton, 1970].

3.2 DIGITAL MODEL-LITERATURE REVIEW

Aquifers encountered in nature are generally complex. The aquifer properties vary from place to place. Such aquifers are called non-homogeneous. Further, some properties such as aquifer transmissibility may vary depending on the direction. Such aquifers are called anisotropic. The boundaries are generally irregular and the boundary conditions are not generally well defined. It is very difficult to apply simple analytical methods in such situations. Numerical methods are generally used along with digital computer to solve such problems.

With the widespread availability of digital computers has come the development of mathematical models of aquifers. Applications are expanding, programming techniques are steadily improving, and computer capabilities are growing so that it is safe to say that almost any type of ground water situation can be studied by means of a digital computer model [Kleinecke, 1971].

There is voluminous literature on mathematical modelling, analog and digital computers applied to ground water problems.

Prickett and Lonnquist (1968) gave a comparative study of analog and digital simulation technique applied to various situation.

Pinder and Bredehoeft (1968) discussed the application of the digital computer for aquifer evaluation.

Rushton and Bannister (1970) reported on slow time resistance capacitance analog as an alternative to usual fast time analog.

Lakshminarayana (1971) reviewed electric analog model for management of aquifers with the help of some examples of mathematical models for simple and complex geometric boundaries. According to him the models can be useful if the historical data are reliable. Reliable analytical, analog and digital models can then be developed for efficient management of the aquifers.

Cooley and Sinclair (1976) investigated some of the methods and conditions necessary to determine bounds on values of the hydrogeologic parameters which characterise a model of steady state area near surface ground water flow.

Richard L. Cooley (1977) developed a nonlinear least squares solution for the hydrogeologic parameters, sources and sinks, and boundary fluxes contained in the equations approximately governing two-dimensional or radial steady state ground water motion, through use of a linearization

and iteration procedure applied to the finite element discretization of the problem.

Trescott, P.C. and S.P. Larson (1977) compared the efficiency of line successive over relaxation with a two-dimensional correction procedure (2DC), the iterative, alterating direction implicit procedure (ADI), and the strongly implicit procedure (SIP) to solve finite difference equation used to simulate several ground water reservoirs.

McElwee, D. Carl and M. Arif Yukler (1978) studied the systems response to various parameters. It is shown here how to evaluate the perturbed hydraulic head for a small change in aquifer parameter by means of a first-order sensitivity formation.

Prickett (1979) addressed in his paper both the pros and cons of ground water modelling and presented from a neutralists stand point.

Cooley, R.L. (1979) applied techniques of nonlinear regression to estimate the hydrologic parameters (values of hydraulic conductivity or transmissibity), recharge, discharge, and boundary fluxes for steady ground water flow models of two field areas; Truckee Meadows, Nevada, and a cross section in the Hula Basin Israel.

James and Charles (1980) gave an over view of ground water modelling. The same authors discussed the different approaches to be used in the model. They said that for any

given class of problems the choice of the best approach depends on the processes being modeled, the accuracy desired and the effort that can be expanded on obtaining a solution.

They in the paper represented the use of a ground water flow model to analyse an aquifer system composed of glaciofluvial deposits.

Munter and Anderson (1981) developed a model to estimate the additional data ''seepage rate'' for the Bas Lake and Nepco Lake, Wisconsin.

Kant, Naney and Witz (1982) demonstrated the application of a predictive ground water potentiometric head model to estimate the profitability of irrigation in constrast to that of dry land forming.

Keating (1982) used a lumped parameter model to explain an usual chalk aquifer consisting of a thin zone of high storage and transmissivity whose response of small annual fluctuations and high stream flows were considered to be anamolous.

Chu, Wen-sen and Robert Willis (1984) presented a simpler alternative which permits an easy direct solution of the Bousnesque equation. They used a forward in time, central in space (FTCS) explicit finite difference method in the simulation model.

Paul Richard Eyre (1985) simulated the flow of ground water and the effects of future water development using AQIFEM, a two dimensional finite element flow model, modified for aquifers containing a sea water interface in south-eastern Oahu, Hawaii.

3.3 MATHEMATICAL MODEL

In applying a digital model the aquifer is first descretized by superimposing a grid of horizontal and vertical lines in the finite difference method~~s~~. The intersection of the grid lines is termed as nodes.

The flow equation is then used for each node. The flow equation is based on the equation of continuity and Darcy's law. The equation of continuity can be written as,

Inflow - Outflow = Change in storage.

This relation with Darcy's law yields the equation

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + q - r$$

where,

T = transmissibility of the aquifer in the x and y direction in the horizontal plane,

S = storage coefficient

q = net ground water withdrawal per unit area

r = leakage into the aquifer per unit area

$$\left[\ r = \frac{K'}{b'}(H - \cancel{\phi}\,h)\ \right]$$

K' = coefficient of permeability of the overlying semipervious aquifer (m/day)

b' = the thickness of the overlying semipervious aquifer (metre)

H = head in the overlying aquifer (metre)

h = head in the main aquifer

x & y = rectangular coordinates

t = time coordinate.

For each node this equation is written. The differentials ∂x and ∂y and ∂t are approximated by differences Δx, Δy and Δt. The discretized model is a reasonable representation of the contiuous system provided $\Delta x, \Delta y$ are small compared to total area of the aquifer.

The difference equation for each node can be derived either from the differential equation given above or from physical considerations using Darcy's law and continuity equation. In the implicit method the space derivatives are replaced by finite differences at the time at which the heads are to be calculated. This involves a set of simultaneous equations but the advantage in this method is that it is unconditionally stable regardless the size of the time increment.

Using an implicit finite difference scheme for the present problem, we get the following dquations (Prickett,197[illegible]).

$$T_{i-1,j}\left(\frac{h_{i-1,j}-h_{i,j}}{\Delta x^2}\right) + T_{i,j}\left(\frac{h_{i+1,j}-h_{i,j}}{\Delta y^2}\right)$$

$$+ T_{i,j}\left(\frac{h_{i,j+1}-h_{i,j}}{\Delta x^2}\right) + T_{i,j-1}\left(\frac{h_{i,j-1}-h_{i,j}}{\Delta y^2}\right)$$

$$= S_{i,j}\left(\frac{h_{i,j}-h\emptyset_{i,j}}{\Delta t}\right) + \frac{Q_{i,j}}{\Delta x \Delta y} - \frac{R_{i,j}}{\Delta x \Delta y}$$

where,

$\Delta x, \Delta y$	=	finite difference grid size in the x and y directions (metre)
i,j	=	column and row index of a node (i,j)
Δt	=	time increment elapsed since last calculation of heads(day)
$h\emptyset_{i,j}$	=	calculated head at the previous time increment at node (i,j) (metre)
$h_{i,j}$	=	calculated head at the present time increment at the node (i,j) (metre)
$T_{i,j}$	=	transmissibility of the branches between nodes (i,j) and (i+1,j) and between nodes (i,j) and (i,j+1). The transmissibility of a branch between any two nodes is taken to be the average of the values at these two nodes (m^2/day)
S_{ij}	=	storage coefficient at the node (i,j) (dimensionless)
$Q_{i,j}$	=	net withdrawal rate from the element of the aquifer centered at(i,j)(m^3/day)
$R_{i,j}$	=	leakage into the element of an aquifer centred at (i,j)(m^3/day).

$$R_{i,j} = r_{i,j} \Delta x \Delta y$$

$$r_{ij} = \frac{K'}{b'} (H_{ij} - h_{i,j})$$

$$RFL = \frac{K'}{b'} \Delta x \Delta y = \text{Leakage factor.}$$

The equation is written for each node which results in a set of simultaneous equations.

Many methods are available for solving a set of simultaneous equations. Some of these methods are the successive over relaxation method, alternating direction implicit method, and others. The simplest one is successive over relaxation method, but it is adequate for small size problems. In the present problem a modified version of iterative alternating direction implicit method (Pricket, 1975) is used.

A computer programme written by Mr. T.A. Prickett and C.G. Lonnquist of Illinois State Water Survey, Urbana, Illinois was adapted for the problems encountered in the MRBC Command area,

CHAPTER IV

ANALYSIS AND DISCUSSION OF RESULTS

4.1 INTRODUCTION

The work done for the control of waterlogging for Mahi Right Bank Canal Command area is presented in this chapter. Table 4.1 presents the history matching to obtain the estimates of S,T,L and Q parameter values for particular element represented by a node. In order to make sensitivity analysis the basin is divided into three zones. Table 4.2 shows the results for the average head values for average values of the parameters. In order to understand the effect of different boundary conditions, the sensitivity analysis of the parameter is repeated for different boundary conditions. Table 4.9 presents the situation of water table below ground level and pumpage required to bring down the water table below ground level by 3 metres and 6 metres. All the work done is discussed below in detail.

4.2 HISTORY MATCHING:

The total area of the Mahi Right Bank Canal Command area is 3.6×10^7 sq.km. It is covered by a network of 13x11 grid lines(Fig. 4.1). Grid spacing taken here is 6000 m. At each node a well is assumed covering 3.6×10^7 sq. m. area.For matching historical data several years of data are required for the reliability of the models. Unfortunately only two years data were available . That is the heads (with respect to mean

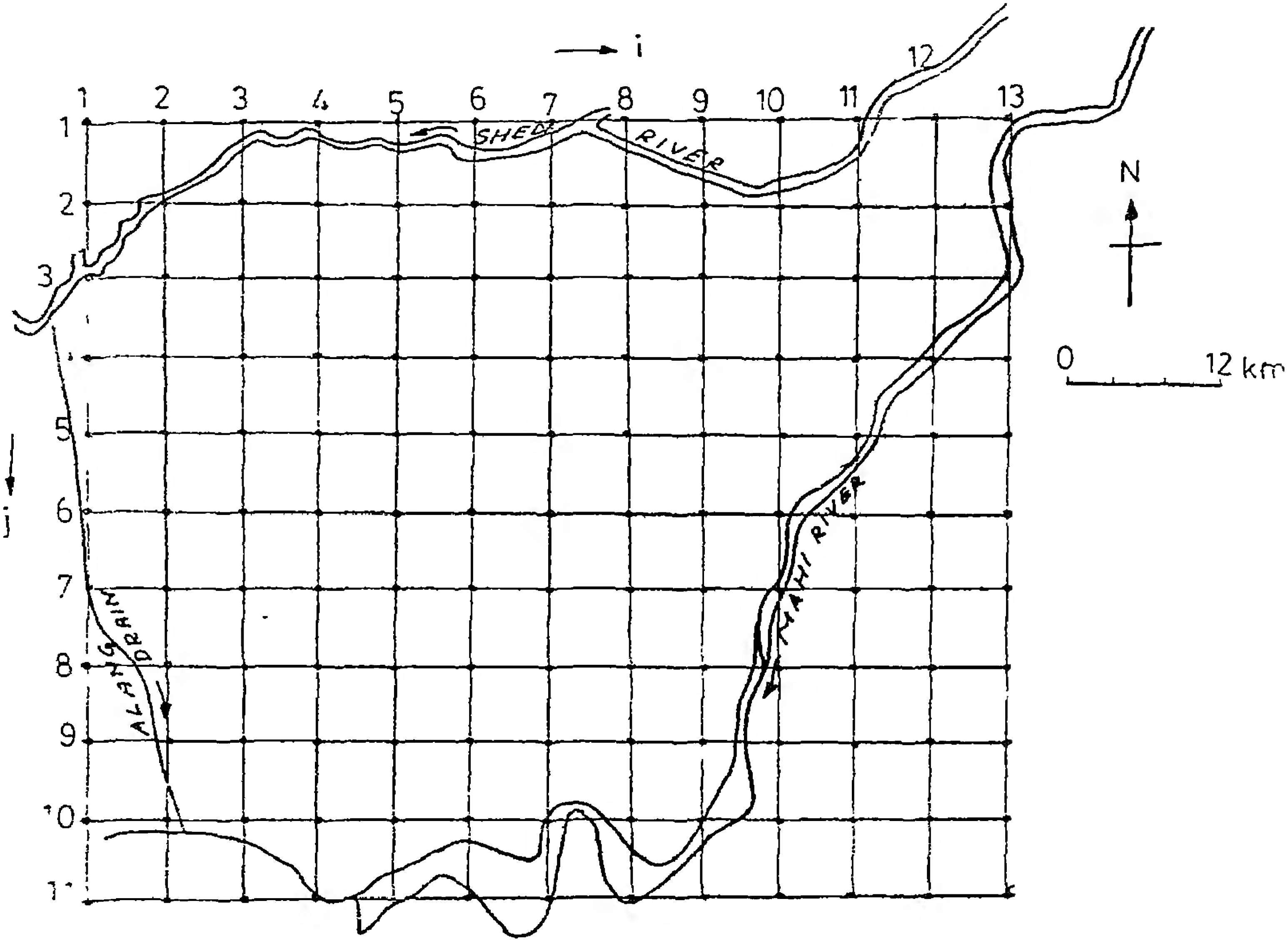

Fig. 4·1 Grid configuration for MRBC command area aquifer model

seal level) of 1979 and 1980 were available. Approximate values of transmissivity, storage coefficient, leakage etc. were also available. Based on this information, the parameters, mentioned above, were roughly fixed for each node. Taking 1979 heads as input, the heads after one year (for 1980) were computed with the help of computer. It is obvious that in first shot the 1980 heads value (computed) will not be matching with the 1980 heads value (observed). So, for matching the history data the values of parameters (S, T, Q & L) were varied in a fixed range. The method adopted here is just trial and error and several runs were taken for matching the computed 1980 heads with observed 1980 heads. Table 4.1 represents the heads of 1979 (observed), 1980 (observed) and 1980 computed for each node.

In order to study the results to changes in the input parameters, sensitivity analysis is required. The Mahi Right Bank canal command area being large it was decided to divide this into 3 zones based on S and T values and make the sensitivity analysis for these zones.

Table 4.2 represents the average head observed (1979 and 1980) and head computed. These heads are average values worked out zone-wise from Table 4.1. Using the mathematical model zone wise heads were also recomputed by inputting into the model zonewise average parameters. These are shown in Table 4.3. It may be seen that there is slight difference in the computed heads for the year 1980.

4.3 SENSITIVITY ANALYSIS

For each zone the average value of S,T,Q and L is computed. Taking these values and average head 1979 (observed) as input the heads are computed for 1980. These computed heads are compared with the observed 1980 heads. RUN-A represents computed heads for 1980 for the average conditions of parameters. This is used for the purpose of making comparision with other runs. The procedure adopted for sensitivity analysis is to change one parameter at a time holding all other parameters at their average values. The changes are made within a reasonable range. RUN 1 and RUN 2 are taken after decreasing or increasing the transmissivity values by 50 percent. In RUN 3 and RUN 4 storage coefficient S is decreased or increased by one order of magnitude of the average values. Similarly in RUN 5 and RUN 6 Q (pumpage) is decreased or increased by 50 percent and in RUN 7 and RUN 8, L (leakage) values are decreased or increased by 50 percent of their average values.

The boundary conditions imposed on the model are constant head boundary conditions for evaluating the average parameter values. It is felt that these boundary conditions may not be appropriate all along the boundary. At some places along the boundary it is possible a different type of boundary condition than a constant head boundary condition may be more appropriate. Hence it was decided to study the effect of different types of boundary conditions on the heads inside the

boundary. Three types of boundary conditions were investigated.

1. Constant Head Boundary: - The head is constant along the boundary. This condition is easily imposed by making the storage coefficient S assume a very large value on the boundary.

2. No Flow:- This condition assumes that no flow takes place across the boundary. This condition is fulfilled by taking the transmissivity (T) values as zero on the boundry.

3. Specified Outflow:- This condition assumes that a specified outflow takes place across the boundary. A part to the boundary is assumed to be impervious and on the remaining part flow is allowed to take place across it. This condition is easily imposed by assigning the quantity that flows out across a segment of the boundary as a pumpage assigned to the node nearest to the segment, and the inflow across the segment of the boundary as recharge assigned to the node nearest to that segment.

Sensitivity analysis can also be useful for site - specific applications to indicate what additional data is to be determined and area where additional data are needed.

4.4 CONTROL OF WATERLOGGING

Waterlogging occurs when the water table is zero to 1.5 metres below the ground level. From the model it is possible to ~~computed~~ the year 1980 heads using the 1979 heads.

These heads are measured with respect to mean sea level. We know the geohydrological conditions of the aquifer at different section taken through the MRBC Command area. The ground levels are also known with respect to MSL. Computed heads can therefore be used to find the depth of water table below ground level. In the Table 4.9 the water table below the ground level is shown at each node. It is seen that at many nodes waterlogging has occurred. It is necessary to keep the water table below the ground level at a reasonable depth. One policy can be to keep the water table, say, 3 metres below the ground level. The additional pumpage required to be done in this case is shown in the Table 4.9.

The total ground water required to be pumped is about 454 ~~544~~ MCM per year. This extra water is available for irrigation.

A second policy can be, from the management point of view, to stabilize the water table below ground level at 6 metres. This will yield an additional quantity of about 3960 ~~5840~~ MCM per year which can be used for irrigation.

4.5 DISCUSSION OF RESULTS

4.5.1 MATCHING OF HISTORICAL DATA

The validation of the model is done by matching historical data. For proper validation of ground water models at least 8 to 10 years of data are required. Then half the number of years of data is used for matching and the other half for checking. In the present case only two years data

were available hence the results can not be fully relied upon.

While matching with historical data it is assumed that the heads on the boundaries are constant. But the available data show that appreciable changes in heads occur on the boundaries . For this reason the boundary nodes are omitted in sensitivity analysis. The results of history matching are shown in Table 4.1 node by node. It is seen from the results that inside the boundary the heads of 1980 (observed) are fairly close to the 1980 heads (computed). The various parameters for each of the nodes are shown in column (3), (4), (5) and (6).

As mentioned before for making sensitivity analysis on the parameters the area in divided into three zones. For each zone average values of S, T, Q and L are computed and shown in Table 4.3. Further using the mathematical model the heads computed for each zone for the zonal average parameters are also shown in Table 4.3. As stated above the difference between these heads is small in each zone. These average heads will be used for purposes of comparision later in sensitivity analysis. Also sensitivity analysis has been carried out for different boundary conditions.

4.5.2 SENSITIVITY ANALYSIS

Table 4.4 shows the results of sensitivity analysis for constant head boundary conditions. In this Table RUN 1

represents results for $T = 0.5\ T_{Av}$ and all other parameters are held at their average values. Similarly for the other RUNs the changed value of parameter is shown under the particular RUN in the table.

By studying the results shown in this table (Table 4.4) the following conclusions may be drawn.

(i) Effect of Variation in T:- The results indicate that zone I and zone II are not affected with variation in T. Zone III is only slightly affected.

(ii) Effect of Variation in S:- The results got after varying the storage coefficient by one order of magnitude above and below the average values show that there is not much change in Zones I and II whereas there is only a slight change of heads in zone III.

(iii) Effect of Variations in Q:- All the three zones are sensitive to changes in Q. Zone II is more sensitive and Zone I is least sensitive.

(iv) Effect of Variation in L:- Zone II is more sensitive than Zone III. Zone I is the least sensitive.

Thus it may be stated that in general the parameters Q and L are more sensitive than the parameters S and T. Further Zone II is more sensitive to changes in Q and L compared to Zone III and Zone I is the least sensitive. Thus more care and effort should be exercise in collecting data on Q and R than on S and T.

(v) Effect of Boundary Conditions:- In order to see the sensitivity of boundary conditions, different boundary conditions were considered. The results for the three different boundary conditions are shown in the Tables 4.4, 4.5, 4.7. It is seen from the results that changes in boundary conditions do not affect the computed heads inside the boundary much. This is because the grid size is fairly large (6000 m x 6000 m) because of which the inside points are far removad from the boundary and hence changes in boundary conditions are not felt at these points. This would therefore mean that one can perhaps impose very simple boundary conditions such as no flow or constant head boundary conditions (instead of more complex boundary conditions such as mixed flow condition) and still get acceptable results as long as the boundaries are far away from the point of interest.

4.6 ANTIWATERLOGGING EFFECT

As has already been mentioned one of the antiwaterlogging measure is by proper management of ground water. Having developed a mathematical model for the study area including validation of model and sensitivity analysis,we can say that we have an operational model for the purpose of ground water management to control waterlogging. Using the model we can determine how much pumping should be done at each node to see that water table is lower down to say 3 m below ground level. Table 4.9 shows these results. It is seen from this

Table that the net quantity of water that is required to be pumped from the entire area comes to about 454 MCM. This can be considered as extra ground water potential that is available for irrigation. As an alternative policy, we may decide that instead of lowering the water table only to 3 m below ground level we may lower it to 6 m below ground level. This will not only remove waterlogging but also give much more additional ground water. From the table it is seen that for this policy the net water available is about 3960 MCM per year. It is emphasized that this net quantity of pumpage should be over and above the pumpage required to account for (i) the fraction of applied ground water returning back as recharge after irrigation and (ii) the reduction in non-beneficial evapotranspiration due to lower ground water table.

TABLE 4.1: RESULTS OF MATCHING HISTORICAL DATA

I	J	S	T	Q	L	Heads 1979 (observed)	Heads 1980 (observed)	Heads 1980 (computed)
1	2	3	4	5	6	7	8	9
1	1	2.78×10^{-3}	0.0	0.0	0.0	0.0	0.0	0.0
1	2	2.78×10^{-3}	0.0	0.0	0.0	12.1	13.6	12.1
1	3	2.78×10^{-13}	1400.0	0.463×10^{5}	115200.0	12.1	13.6	12.1
1	4	2.78×10^{13}	1070.0	0.463×10^{5}	115200.0	13.6	13.1	13.6
1	5	2.78×10^{13}	750.0	0.463×10^{5}	115200.0	9.8	9.2	9.8
1	6	2.78×10^{13}	620.0	0.358×10^{5}	115200.0	8.7	9.2	8.7
1	7	2.78×10^{13}	600.0	0.358×10^{5}	115200.0	7.6	7.8	7.6
1	8	2.78×10^{-3}	0.0	0.0	0.0	7.5	8.8	7.6
1	9	2.78×10^{-3}	0.0	0.0	0.0	2.5	3.6	2.5
1	10	2.78×10^{-3}	0.0	0.0	0.0	0.0	0.0	0.0
1	11	2.78×10^{-3}	0.0	0.0	0.0	0.0	0.0	0.0
2	1	2.78×10^{-3}	0.0	0.0	0.0	20.8	21.5	22.8
2	2	2.78×10^{13}	1863.0	0.463×10^{5}	115200.0	18.2	18.2	18.2
2	3	2.0×10^{-2}	1550.0	0.463×10^{5}	115200.0	17.0	18.2	17.8
2	4	1.75×10^{-2}	1300.0	0.463×10^{5}	115200.0	17.4	18.0	18.1
2	5	1.75×10^{-2}	1080.0	0.462×10^{5}	115200.0	16.8	15.0	15.4
2	6	2.0×10^{-2}	900.0	0.368×10^{5}	115200.0	15.9	14.9	14.8
2	7	2.6×10^{-2}	620.0	0.368×10^{5}	115200.0	10.3	10.4	10.0

Contd....

Table 4.1 contd...

1	2	3	4	5	6	7	8	9
2	8	$2.78x10^{13}$	1250.0	$0.368x10^{5}$	115200.00	7.50	9.80	7.50
2	9	$2.78x10^{13}$	931.0	$0.368x10^{5}$	115200.00	2.50	3.60	2.50
2	10	$2.78x10^{13}$	0.0	0.0	0.00	11.50	11.50	11.50
2	11	$2.78x10^{-3}$	0.0	0.0	0.00	0.00	0.00	0.00
3	1	$2.78x10^{13}$	1700.0	$0.468x10^{5}$	115200.00	20.80	21.50	20.80
3	2	$2.78x10^{13}$	1960.0	$0.468x10^{5}$	115200.00	21.60	21.50	21.60
3	3	$2.0 x10^{-3}$	1600.0	$0.468x10^{5}$	115200.00	-21.10	21.90	21.51
3	4	$2.30x10^{-3}$	1240.0	$-0.97 x10^{4}$	100.00	-19.80	22.40	22.09
3	5	$2.30x10^{-3}$	960.0	$0.572x10^{5}$	115200.00	17.30	17.80	19.01
3	6	$2.61x10^{-3}$	1000.0	$0.572x10^{5}$	115200.00	16.40	16.20	18.90
3	7	$2.61x10^{-3}$	1800.0	$0.359x10^{5}$	115200.00	-12.20	14.70	14.58
3	8	$2.78x10^{-3}$	1900.0	$0.359x10^{3}$	145200.00	-8.10	10.00	9.55
3	9	$2.78x10^{-3}$	1700.0	$0.359x10^{5}$	115200.00	-9.60	10.20	9.99
3	10	$2.78x10^{13}$	0.0	0.0	0.00	11.50	11.20	11.50
3	11	$2.78x10^{-3}$	0.0	0.0	0.00	2.10	4.10	2.10
4	1	$2.78x10^{13}$	1930.0	$0.468x10^{5}$	115200.00	23.70	23.30	23.70
4	2	$2.00x10^{-3}$	1240.0	$0.468x10^{5}$	115200.00	23.70	23.30	23.32
4	3	$2.00x10^{-3}$	1400.0	$-0.93x10^{4}$	0.00	24.00	25.60	25.65
4	4	$1.61x10^{-3}$	1100.0	$0.572x10^{5}$	115200.00	24.00	23.40	23.50
4	5	$1.61x10^{-3}$	900.0	$0.572x10^{5}$	115200.00	19.30	19.50	19.30
4	6	$2.61x10^{-3}$	1240.0	$0.572x10^{5}$	115200.00	19.60	16.00	16.02
4	7	$2.61x10^{-3}$	2240.0	$0.572x10^{5}$	115200.00	11.60	13.30	13.29

Contd.....

Table 4.1 contd...

1	2	3	4	5	6	7	8	9
4	8	$2.78x10^{-3}$	2710.0	$0.338x10^{5}$	5500 .00	0.20	3.00	3.17
4	9	$2.78x10^{-3}$	2720.0	$0.738x10^{5}$	5200 .00	2.00	3.90	4.20
4	10	$2.78x10^{-3}$	0.0	$0.338x10^{5}$	10000.00	3.10	4.10	4.16
4	11	$2.78x10^{13}$	0.0	$0.368x10^{5}$	115200.00	2.10	4.10	2.10
5	1	$2.78x10^{13}$	310.0	$0.578x10^{5}$	115200.00	26.60	24.80	26.60
5	2	$2.00x10^{-3}$	620.0	$0.200x10^{6}$	121200.00	26.60	24.80	24.97
5	3	$2.00x10^{-3}$	1000.0	$-0.65x10^{3}$	0.00	25.40	27.20	27.33
5	4	$2.00x10^{-3}$	1200.0	$-0.308x10^{3}$	0.00	23.90	26.90	26.59
5	5	$2.30x10^{-2}$	1400.0	$0.100x10^{4}$	1000.00	12.40	17.60	17.50
5	6	$2.61x10^{-3}$	2170.0	$-0.180x10^{6}$	115200.00	13.70	17.00	17.13
5	7	$2.61x10^{-3}$	2430.0	$0.358x10^{4}$	115200.00	10.50	10.10	10.41
5	8	$2.78x10^{-3}$	3420.0	$-0.500x10^{3}$	0.00	4.50	6.50	6.24
5	9	$2.78x10^{-3}$	2350.0	$0.547x10^{4}$	115200.00	4.60	6.10	5.99
5	10	$2.78x10^{13}$	0.0	0.0	7500 .00	2.50	2.80	2.59
5	11	$2.78x10^{13}$	0.0	$0.578x10^{5}$	115200.00	2.50	3.80	2.50
6	1	$2.78x10^{13}$	300.0	$0.578x10^{5}$	115200.00	29.60	29.10	29.60
6	2	$2.00x10^{-3}$	310.0	$0.158x10^{6}$	115200.00	30.60	29.10	29.25
6	3	$2.00x10^{-3}$	930.0	$0.278x10^{3}$	0.00	26.80	27.40	27.06
6	4	$2.30x10^{-3}$	1350.0	$0.57x10^{5}$	115200.00	26.00	26.00	26.29
6	5	$2.30x10^{-3}$	2170.0	$0.578x10^{5}$	115200.00	19.20	22.50	22.15
6	6	$2.61x10^{-3}$	2950.0	$-0.230x10^{3}$	0.00	13.60	17.50	17.23

Contd.....

Table 4.1 contd...

1	2	3	4	5	6	7	8	9
6	7	2.61×10^{-3}	3730.0	-0.578×10^{5}	5200.00	15.10	15.90	15.23
6	8	2.78×10^{-4}	4040.0	-0.100×10^{5}	10200.00	6.40	8.20	8.45
6	9	2.78×10^{-3}	3730.0	0.578×10^{5}	115200.00	5.20	6.10	6.09
6	10	2.78×10^{13}	3670.0	0.578×10^{5}	115200.00	8.60	8.60	8.60
6	11	2.78×10^{-3}	0.0	0.0	0.00	8.60	8.60	8.60
7	1	2.78×10^{13}	600.0	0.578×10^{5}	115200.00	2.60	32.30	32.60
7	2	2.00×10^{-3}	620.0	0.578×10^{5}	115200.00	33.60	32.30	32.48
7	3	2.00×10^{-3}	1320.0	0.100×10^{5}	2200.00	29.00	30.00	30.22
7	4	1.61×10^{-3}	1780.0	-0.250×10^{4}	0.00	26.00	29.20	28.96
7	5	1.61×10^{-3}	2480.0	-0.350×10^{5}	5200.00	20.70	23.30	23.37
7	6	2.61×10^{-3}	3250.0	0.0	17200.00	11.90	13.30	13.56
7	7	2.61×10^{-3}	3880.0	0.557×10^{5}	115200.00	15.20	14.30	14.61
7	8	2.78×10^{-3}	4500.0	0.557×10^{3}	45200.00	6.60	7.40	7.39
7	9	2.78×10^{-3}	4300.0	0.557×10^{3}	200.00	6.60	7.30	7.29
7	10	2.78×10^{13}	4000.0	0.557×10^{5}	115200.00	5.10	6.10	5.10
7	11	2.78×10^{-3}	0.0	0.0	0.0	5.10	6.10	5.10
8	1	2.78×10^{13}	900.0	0.578×10^{5}	115200.0	35.20	34.90	35.20
8	2	2.30×10^{-3}	1090.0	0.578×10^{5}	115200.0	35.20	34.90	34.73
8	3	2.00×10^{-3}	1415.0	-0.170×10^{6}	85200.0	33.20	35.10	35.19
8	4	2.30×10^{-3}	1700.0	-0.443×10^{5}	4200.0	27.20	33.40	33.90
8	5	2.30×10^{-3}	1850.0	-0.443×10^{5}	8200.0	25.30	28.00	28.07

Contd......

Table 4.1 contd...

1	2	3	4	5	6	7	8	9
8	6	2.61×10^{-3}	2100.0	-0.443×10^{5}	22200.00	16.60	18.70	18.70
8	7	2.61×10^{-3}	2800.0	0.557×10^{5}	115200.00	14.70	14.50	14.20
8	8	2.78×10^{-3}	4500.0	0.557×10^{5}	115200.00	8.60	8.50	8.37
8	9	2.78×10^{-3}	4500.0	-0.350×10^{6}	515200.00	8.20	8.90	8.80
8	10	2.78×10^{13}	4600.0	0.557×10^{5}	115200.00	3.50	4.20	3.50
8	11	2.78×10^{13}	0.0	0.0	115200.00	3.50	4.20	3.50
9	1	2.78×10^{-3}	0.0	-0.355×10^{4}	0.00	38.30	39.20	39.10
9	2	2.78×10^{13}	1400.0	0.443×10^{5}	115200.00	38.30	39.20	38.30
9	3	3.08×10^{-3}	1800.0	-0.303×10^{6}	115200.00	39.80	41.90	42.30
9	4	2.30×10^{-3}	2080.0	-0.643×10^{6}	115200.00	39.20	37.80	37.66
9	5	2.30×10^{-3}	2200.0	-0.443×10^{5}	115200.00	26.50	29.30	29.67
9	6	2.61×10^{-3}	1930.0	-0.443×10^{5}	15200.00	19.90	22.20	22.44
9	7	1.11×10^{-4}	1550.0	0.557×10^{2}	115200.00	14.40	15.50	15.30
9	8	2.78×10^{-3}	2500.0	-0.557×10^{5}	15200.00	9.80	11.30	11.63
9	9	2.78×10^{-3}	2500.0	-0.357×10^{5}	15200.00	5.60	7.40	7.56
9	10	2.78×10^{13}	4030.0	0.557×10^{5}	115200.00	1.90	2.00	1.90
9	11	2.78×10^{-3}	0.0	0.0	0.00	1.90	2.00	1.90
10	1	2.78×10^{-3}	0.0	0.0	0.00	38.40	39.20	38.40
10	2	2.78×10^{13}	1700.0	0.445×10^{5}	115200.00	38.40	39.20	38.40
10	3	2.00×10^{-3}	2300.0	0.445×10^{5}	115200.00	42.30	42.90	42.96
10	4	2.20×10^{-3}	3410.0	0.445×10^{5}	115200.00	37.20	37.90	37.99
11	5	2.30×10^{-3}	2800.0	0.445×10^{5}	115200.00	33.00	32.70	32.52

Contd.....

Table 4.1 contd. ..

1	2	3	4	5	6	7	8	9
10	6	2.78×10^{13}	1860.0	0.445×10^{5}	115200.00	22.40	23.30	22.40
10	7	2.78×10^{13}	900.0	0.495×10^{5}	115200.00	22.40	23.40	22.40
10	8	2.78×10^{13}	1000.0	0.445×10^{5}	115200.00	8.60	8.60	8.60
10	9	2.78×10^{13}	2400.00	0.445×10^{5}	115200.00	4.60	4.60	4.60
10	10	2.78×10^{13}	0.0	0.0	0.00	4.60	4.60	4.60
10	11	2.73×10^{-3}	0.0	0.0	0.00	0.00	0.00	0.00
11	1	2.78×10^{13}	0.0	0.894×10^{5}	115200.00	57.80	58.10	57.80
11	2	2.78×10^{-3}	0.0	0.894×10^{5}	115200.00	46.30	46.20	46.11
11	3	2.78×10^{-3}	0.0	0.443×10^{5}	115200.00	43.30	43.80	44.09
11	4	2.78×10^{-3}	0.0	0.443×10^{5}	115200.00	39.30	39.50	39.66
11	5	2.78×10^{-3}	0.0	0.443×10^{5}	115200.00	35.00	34.30	34.56
11	6	2.78×10^{-3}	0.0	0.0	0.00	22.40	23.30	22.40
11	7	2.78×10^{-3}	0.0	0.0	0.00	22.40	23.30	22.40
11	8	2.78×10^{-3}	0.0	0.0	0.00	8.60	8.60	8.60
11	9	2.78×10^{-3}	0.0	0.0	0.00	4.60	4.60	4.60
11	10	2.78×10^{-3}	0.0	0.0	0.00	0.00	0.00	0.00
11	11	2.78×10^{-3}	0.0	0.0	0.00	0.00	0.00	0.00
12	1	2.78×10^{-3}	0.0	0.894×10^{5}	115200.00	56.70	56.50	56.62
12	2	2.78×10^{-3}	0.0	-0.894×10^{5}	30200.00	53.60	56.50	56.56
12	3	2.78×10^{-3}	0.0	-0.894×10^{5}	20200.00	49.30	53.90	54.02
12	4	2.78×10^{13}	0.0	0.443×10^{5}	115200.00	40.00	40.00	40.00

Contd.....

Table 4.1 contd...

1	2	3	4	5	6	7	8	9
12	5	$2.78x10^{-3}$	0.0	0.0	0.0	35.00	34.80	35.00
13	1	$2.78x10^{13}$	0.0	$0.894x10^{5}$	115200.0	56.50	56.50	56.50
13	2	$2.78x10^{13}$	0.0	$0.894x10^{5}$	115200.0	53.70	53.70	53.70
13	3	$2.78x10^{13}$	0.0	0.0	115200.0	49.30	53.90	53.30
13	4	$2.78x10^{-3}$	0.0	0.0	0.0	40.00	40.00	40.00

NOTE: Nodes not included in the table are outside of the boundary.

TABLE 4.2: ZONEWISE AVERAGE VALUES

	Heads 1979 (Observed)	Heads 1980 (Observed)	Heads 1980 (Computed)
Zone I	18.11	18.68	18.59
Zone II	9.59	10.99	10.01
Zone III	29.57	30.75	30.83

~~[Irrigation Commission Report, 1972]~~

TABLE 4.3 : RUN-A. MODEL RESULTS FOR AVERAGE VALUES OF PARAMETERS FOR CONSTANT HEAD BOUNDARY CONDITION

	T (m^2/day)	S (Dimensionless)	Q (m^3/day)	L (m^2/day)	Head 1979 (observed)	Head 1980 (Observed)	Head 1980+ (Computed)
Zone I	1257.0	0.43×10^{-2}	19592.0	89252.0	18.11	18.680	18.01
Zone II	3325.0	0.27×10^{-2}	-5416.0	77652.0	9.59	10.995	10.86
Zone III	1714.0	0.21×10^{-2}	-45777.0	63389.0	29.57	30.750	30.05

\+ Heads recomputed using average value of S,T,Q and L parameters in each zone.

TABLE 4.4: SENSITIVITY ANALYSIS FOR CONSTANT HEAD BOUNDARY CONDITION

RUN No.	Zone I		Zone II		Zone III	
	Observed Head 1980	Computed Head 1980	Observed Head 1980	Computed Head 1980	Observed Head 1980	Computed Head 1980
RUN 1 ($T = 0.5\ T_{AV}$)	18.68	17.98	10.995	10.86	30.75	30.14
RUN 2 ($T = 1.5\ T_{AV}$)	18.68	17.99	10.995	10.85	30.75	30.16
RUN 3 ($S = 0.1 \times S_{AV}$)	18.68	17.99	10.995	10.86	30.75	30.16
RUN 4 ($S = 10.0 \times S_{AV}$)	18.68	17.99	10.995	10.86	30.75	30.16
RUN 5 ($Q = 0.50 \times Q_{AV}$)	18.68	18.05	10.995	10.19	30.75	29.84
RUN 6 ($Q = 1.5 \times Q_{AV}$)	18.68	17.93	10.995	11.33	30.75	30.64
RUN 7 ($L = 0.50 \times L_{AV}$)	18.68	17.87	10.995	11.98	30.75	30.86
RUN 8 ($L = 1.5 \times L_{AV}$)	18.68	18.03	10.995	10.36	30.75	29.86

TABLE 4.5 : RUN B: MODEL RESULTS FOR AVERAGE VALUES OF PARAMETERS FOR NO FLOW BOUNDARY CONDITION

	T	S	Q	L	Head 1979 (observed) m	Head 1980 (Observed) m	Head 1980 (computed)
Zone I	1257.0	0.43×10^{-2}	19592.0	89252.0	18.11	18.680	17.99
Zone II	3325.0	0.27×10^{-2}	- 5416.0	77652.0	9.59	10.995	10.74
Zone III	1714.0	0.21×10^{-2}	-45777.0	63389.0	29.57	30.75	30.04

TABLE 4.6: SENSITIVITY ANALYSIS FOR NO FLOW BOUNDARY CONDITION

RUN NO.	Zone I		Zone II		Zone III	
	Observed Head 1980	Computed Head 1980	Observed Head 1980	Computed Head 1980	Observed Head 1980	Computed Head 1980
RUN 1 ($T = 0.5\ T_{AV}$)	18.68	17.99	10.995	10.75	30.75	30.13
RUN 2 ($T=1.5\ T_{AV}$)	18.68	17.99	10.995	10.86	30.75	29.87
RUN 3 ($S=0.1xS_{AV}$)	18.68	17.99	10.995	10.85	30.75	29.87
RUN 4 ($S=10.0xS_{AV}$)	18.68	17.99	10.995	10.85	30.75	29.87
RUN 5 ($Q=0.5xQ_{AV}$)	18.68	18.05	10.995	10.20	30.75	29.33
RUN 6 ($Q=1.5xQ_{AV}$)	18.68	17.94	10.995	11.37	30.75	30.69
RUN 7 ($L=0.5xL_{AV}$)	18.68	17.93	10.995	12.03	30.75	30.76
RUN 8 ($L=1.5xL_{AV}$)	18.68	18.03	10.995	10.36	30.75	29.36

TABLE 4.7 : RUN C: MODEL RESULTS FOR AVERAGE VALUE OF PARAMETERS FOR SPECIFIED FLOW ACROSS THE BOUNDARY

	T	S	Q	L	Head 1979 (Observed)	Head 1980 (Observed)	Head 1980 (Computed)
Zone I	1257.0	0.43×10^{-2}	19592.0	89252.0	18.11	18.680	17.99
Zone II	3325.0	0.27×10^{-2}	-5416.0	77652.0	9.59	10.995	10.85
Zone III	1714.0	0.21×10^{-2}	-45777.0	63389.0	29.57	30.750	30.07

TABLE 4.8: SENSITIVITY ANALYSIS FOR SPECIFIED FLOW ACROSS THE BOUNDARY

RUN NO.	Zone I		Zone II		Zone III	
	Observed Head 1980	Computed Head 1980	Observed Head 1980	Computed Head 1980	Observed Head 1980	Computed Head 1980
RUN 1 ($T=0.5T_{AV}$)	18.68	17.99	10.995	10.85	30.75	30.15
RUN 2 ($T=1.5\ T_{AV}$)	18.68	17.99	10.995	10.86	30.75	30.23
RUN 3 ($S=0.1xS_{AV}$)	18.68	17.99	10.995	10.86	30.75	30.06
RUN 4 ($S=10.0xS_{AV}$)	18.68	17.99	10.995	10.86	30.75	30.06
RUN 5 ($Q=0.50xQ_{AV}$)	18.68	18.05	10.955	10.21	30.75	29.84
RUN 6 ($Q=1.5xQ_{AV}$)	18.68	17.94	10.955	11.29	30.75	30.58
RUN 7 ($L=0.5xL_{AV}$)	18.68	17.89	10.955	12.06	30.75	30.83
RUN 8 ($L=1.5xL_{AV}$)	10.68	18.03	10.955	10.36	30.75	29.86

TABLE 4.9 : ADDITIONAL WATER AVAILABLE DUE TO LOWERING OF GROUND WATER TABLE

I	J	Ground Water Level (1980)	Ground Level Above MSL	Water Table Depth (below G.L.)	Water Level to be maintained above MSL Case 1[ψ]	Water Level to be maintained above MSL Case 2[ψ]	Pumpage required to lower the water table below ground level Case 1	Pumpage required to lower the water table below ground level Case 2
1	2	3	4	5	6	7	8	9
1	2	12.10	29.60	17.50				
1	3	12.10	33.50	25.40				
1	4	13.60	49.50	34.90				
1	5	9.80	40.00	30.20				
1	6	8.70	9.00	0.30				
1	7	7.60	9.00	1.40				
1	8	7.58	9.10	1.50				
1	9	2.50	8.70	6.20				
2	1	21.50	33.20	11.70				
2	2	18.20	25.60	7.40				
2	3	17.80	29.10	11.30				
2	4	18.07	39.10	21.10				
2	5	15.41	30.00	14.60				
2	6	14.82	~~9.50~~ 14.82	~~5.30~~ 0.00	~~6.50~~ 11.82	~~3.50~~ 8.82	~~59360.00~~ 1530.00	~~1323200.00~~ 3030.00

Contd..

ψ Case 1 - Water table depth to be kept 3m below ground level
ψ Case 2 - Water table depth to be kept 6 m below ground level

Table 4.9 contd...

1	2	3	4	5	6	7	8	9
2	7	10.01	10.50	0.50	7.50	4.50	638240.00	711200.00
2	8	7.50	9.50	2.00	3.50(B)			
2	9	2.50	9.50	7.00				
3	1	20.80	35.60	14.80				
3	2	21.50	30.20	8.60				
3	3	21.51	24.20	2.70	21.20	20.20	10140.00	193700.00
3	4	22.09	24.00	2.00	21.10	18.10	1870.00	2500.00
3	5	18.01	18.01	0.00	15.01	12.01	6420.00	118300.00
3	6	15.90	15.90	0.00	12.90	9.90	1620.00	13560.00
3	7	14.58	14.58	0.00	11.58	8.58	5860.00	503100.00
3	8	9.55	10.10	0.60	7.20	4.20	77634.00	858641.00
3	9	9.99	10.10	0.10	7.00	4.10	85080.00	963100.00
3	10	11.50	11.50	0.00	8.50(B)			
4	1	23.70	36.80	13.10				
4	2	23.32	30.80	7.50				
4	3	25.65	27.20	1.50	24.15	21.15	11350.00	18270.00
4	4	23.50	27.00	3.50		21.15		362800.00
4	5	19.30	19.30	0.00	16.30	13.30	69230.00	809600.00
4	6	15.02	15.40	0.38	12.40	9.40	70250.00	814800.00
4	7	13.28	13.30	0.00	10.30	7.30	60250.00	714800.00
4	8	3.17	15.80	12.60				
4	9	4.20	15.80	11.60				

Contd...

Table 4.9 contd...

1	2	3	4	5	6	7	8	9
4	10	1.70	14.70	10.50				
4	11	2.10	10.30	8.20				
5	1	26.60	39.20	12.60				
5	2	24.97	31.00	6.00				
5	3	27.33	33.20	6.00				
5	4	26.59	23.00	7.40				
5	5	17.50	20.30	2.80	17.40	14.40	1560.00	8850.00
5	6	17.13	19.30	2.20	16.30	13.30	44770.00	560000.00
5	7	10.41	10.41 ~~10.20~~	0.00 ~~0.20~~	7.41 ~~7.20~~	4.41 ~~4.20~~	95750.00 ~~99260.00~~	1713000.00 ~~1722200.00~~
5	8	6.24	39.90	33.60				
5	9	15.00	9.00					
5	10	3.59	14.10	10.50				
5	11	2.50	10.50	8.00				
6	1	29.60	55.00	25.40				
6	2	29.25	33.20	4.00		27.25		400000.00
6	3	27.60	35.60	8.60				
6	4	26.29	30.00	3.30		23.60		620200.00
6	5	22.15	22.90	0.80	20.00	17.00	42790.00	540200.00
6	6	17.23	25.80	8.50				
6	7	16.23	23.40	6.10				
6	8	8.45	10.00	1.55	7.00	4.00	19570.00	288000.00
6	9	6.69	14.30	7.70				

Contd.....

Table 4.9 contd..

1	2	3	4	5	6	7	8	9
6	10	8.60	13.50	14.90		~~2.30~~ 3.30(3)		
7	1	32.60	17.30	37.70				
7	2	32.48	35.60	3.10		29.60		490200.00
7	3	30.22	45.50	15.30				
7	4	28.06	44.90	16.00				
7	5	23.37	36.70	13.30				
7	6	14.56	30.20	15.60				
7	7	14.61	28.50	13.90				
7	8	7.39	29.10	11.70				
7	9	7.29	17.20	10.00				
7	10	5.10	16.20	11.10				
8	1	35.20	93.30	68.10				
8	2	34.73	49.50	14.80				
8	3	35.19	50.00	14.80				
8	4	33.96	36.90	3.00		31.00		44255.70
8	5	28.07	43.50	5.50		27.57		37870.00
8	6	18.70	36.60	18.00				
6	7	14.20	33.50	19.30				
8	8	8.37	28.20	15.80				
8	9	8.88	19.20	10.40				
8	10	3.50	18.30	12.80				
9	1	39.10	110.20	71.10				

Contd......

Table 4.9 contd...

1	2	3	4	5	6	7	8	9
9	2	38.30	73.50	35.20				
9	3	42.30	60.30	18.00				
9	4	37.66	68.60	31.00				
9	5	29.67	42.20	12.50				
9	6	22.44	42.10	19.70				
9	7	15.39	35.30	19.90				
9	8	11.63	29.90	13.30				
9	9	7.56	21.40	13.80				
9	10	1.90	20.70	18.80				
10	1	38.40	123.30	74.90				
10	2	38.40	104.50	63.10				
10	3	42.96	68.90	26.00				
10	4	37.99	69.50	31.50				
10	5	32.52	40.80	8.30				
10	6	22.40	43.20	10.80				
10	7	2.40	39.20	36.80				
10	8	8.60	30.50	21.90				
10	9	4.60	26.50	21.90				
11	1	57.80	93.50	35.70				
11	2	46.11	72.50	26.40				
11	3	44.09	73.80	29.70				
11	4	39.66	70.30	30.70				
11	5	34.56	42.30	7.80				

Contd......

Table 4.9 contd...

1	2	3	4	5	6	7	8	9
12	1	56.62	76.50	19.90				
12	2	56.56	74.00	17.40				
12	3	54.02	72.40	18.40				
12	4	40.00	70.10	30.10				
13	1	56.50	76.80	20.30				
13	2	53.70	75.80	22.10				
13	3	49.30	70.50	21.20				
13	4	40.00	68.70	28.70				

Case 1 – Water table depth to be kept 3 m below ground level
Case 2 – Water table depth to be kept 6 m below ground level

NOTE: Nodes not included in the table are outside of boundary

(B) : Boundary nodes

CHAPTER 5

CONCLUSION AND SUGGESTIONS FOR FURTHER WORK

5.1 CONCLUSION

Irrigation when practised improperly leads to several undesirable results such as waterlogging, salinity, incidence of maleria etc. Present thesis deals with the aspect of waterlogging. Several antiwaterlogging measures such as drainage (surface and subsurface), embankment and other flood protection works (to check inundation of the lands), installation of shallow tube wells, lining of canals (to reduce seepage), suitable cropping pattern (such as switching over to crops which need light irrigation in preference to crops which need heavy irrigation), proper land levelling (to avoid accumulation of water over land), etc., are available. Many or all of these measures may have to be used in any given situation. The present work concentrates only on one method namely control of waterlogging by installation of tube wells and management of ground water. A mathematical model is formulated for this purpose. This model is applied to a specific study area namely Mahi Right Bank Canal Command Area.

Published data available for the MRBC Command area was analysed. In this area after introduction of canal irrigation about 30 years ago there has been a progressive increase in the ground water elevation. Many areas are

gradually coming into the range of waterlogged situation (when the water table below ground level comes to 0 to 1.5 metres below ground level, the area is said to be waterlogged). Efforts have been made by the project authorities to construct drainage network. The progressive increase in the waterlogged area indicates that this is not enough. Along with drainage other methods such as installation of tube wells and large scale pumping of ground water are also required.

The mathematical model developed for the study area was validated using two years of ground water data readily available. It may be noted that one neads about 8 to 10 years of data for ground water simulation. In absence of such a length of data, whatever data was available was used. Before using the validated model for studying the anit-waterlogging measure sensitivity analysis on the parameters of the model was done. Four parameters namely S, T, Q and L were subjected to the sensitivity analysis. It was found that S,T are not very sensitive compare to Q and L. It is therefore necessary to know the data on Q and L more carefully than S and T.

In all,mathematical modeling, determination of suitable boundary conditions have to be decided before validating and using the model. In the present case there was some doubt about the proper boundary conditions to be used. In order to varify the effect of different boundary conditions on the results, three types of boundary conditions were studied.

These are (i) Constant head, (ii) No flow and (iii) No flow on part of the boundary and specified flow on the remaining part of the boundary. It was found that these different boundary conditions do not have much effect on the results when we move away from the boundary. How for away? can be determined by gradually reducing the mesh size. In the present case a mesh size of 6000 m x 6000 m was used. It was found that 3 k m. away from the boundary the affect of boundary conditions is negligible. However one has to reduce the mesh size and recompute the results. This was not attempted in the present thesis for want of time.

The validated model is then used for controlling the ground water table. It was decided to see how much pumpage is needed to lower the ground water table 3 metres below ground level wherever necessary. It was found that 459 ~~544~~ MCM of water per year is required to be pumped for this purpose. This water is of course available for irrigation purpose. It is the experience of the project authorities that during the summer months there is not enough water in the Kandana reservoir of the command area. Therefore, this extra water can be used for irrigation during summer. Of course for meaningful results one has to apply the model not for a year as a whole but monthwise or atleast for quarterly periods. This would require enormous amount of data and analysis. Due to lack of time this was not attempted.

A second policy of lowering ground water table to 6 m below ground level was also studied. This yields about 3960 ~~5840~~ MCM of water per year. This additional water can then be used not only in Summer but also for Rabi irrigation.

5.2 SUGGESTIONS FOR FURTHER WORK

Some of the limitations of the study have already been pointed in the above section. Further work can be directed towards removing these limitations. For example data should be collected atleast monthwise for 8 to 10 years for ground water modeling. Mathematical modeling may then be done and validated using the split sampling method that is about half the available data is used for validating and the other half for checking. It may be necessary to develop two models one for monsoon period and another for non-monsoon period. The effect of boundary condition should be more thoroughly investigated using smaller grid intervals near the boundary.

From the present investigation it has been found that Q and L are more sensitive than S and T. It is therefore necessary to check and to see whether the available data on Q and L are quite reliable. Further the grid size used in the present model namely 6000 m x 6000 m is rather coarse. It may be necessary to reduce this to 1000 m x 1000 m. This would entail collection of more data but the results will be more realistic.

Finally it is necessary to update the model periodically by using the new data as and when they become available. It has been the experience of many ground water modelers that the models requires changes as new data become available.

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